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Joule Heating and Runaway Electron Acceleration in a Solar Flare

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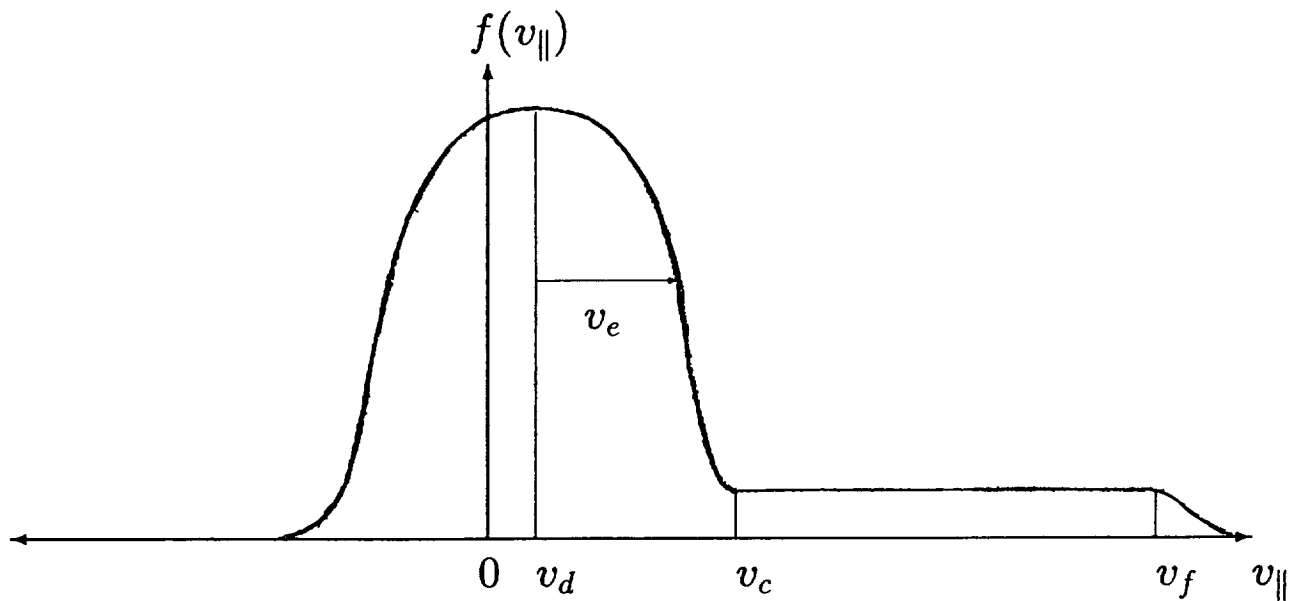
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Abstract

The hard and soft X-ray and microwave emissions from a solar flare (May 14, 1980) have been analyzed and interpreted in terms of Joule heating and runaway electron acceleration in one or more current sheets. It is found that all three emissions can be generated with sub-Dreicer electric fields. The soft X-ray emitting plasma can only be heated by a single current sheet if the resistivity in the sheet is well above the classical, collisional resistivity of a 10^7 K, 10^{11} cm $^{-3}$ plasma. If the hard X-ray emission is from thermal electrons, anomalous resistivity or densities exceeding 3×10^{12} cm $^{-3}$ are required. If the hard X-ray emission is from nonthermal electrons, the emissions can be produced with classical resistivity in the current sheets if the heating rate is ~ 4 times greater than that deduced from the soft X-ray data (with a density of 10^{10} cm $^{-3}$ in the soft X-ray emitting region), if there are at least 10^4 current sheets, and if the plasma properties in the sheets are characteristic of the "superhot" plasma observed in some flares by Lin *et al.* (1981, *Ap. J. Lett.* **251**, L109) and with *Hinotori*. Most of the released energy goes directly into bulk heating, rather than accelerated particles.

ELECTRON RUNAWAY "BASICS"



$$v_e = \sqrt{\frac{kT}{m}}$$

$$W_c = \frac{1}{2}mv_c^2$$

Dreicer Electric Field: $E_D = \frac{m}{e}v_e\nu_e$

$$\frac{E_D}{E} = \frac{v_e}{v_d} = \left(\frac{v_c}{v_e}\right)^2 = \frac{2W_c}{kT}$$

Observable Quantities

$$W_f = (\gamma_f - 1)mc^2$$

HEATING AND ACCELERATION RATES

(see Holman 1985, *Ap. J.*, **293**, 584)

Joule Heating Rate $Q = sJEV_J$ ($s = \#$ of sheets)

Sheet Volume $V_J = A\delta r$, where δr is constrained by Ampere's Law.

$$E = \eta J$$

$$Q = 1.11 \times 10^{21} A_{18} B_2 T_7^{1/2} s \left(\frac{v_d}{v_e}\right) \nu_e \text{ erg s}^{-1}$$

Runaway Acceleration Rate $\dot{N} = s\gamma n_s V_J$

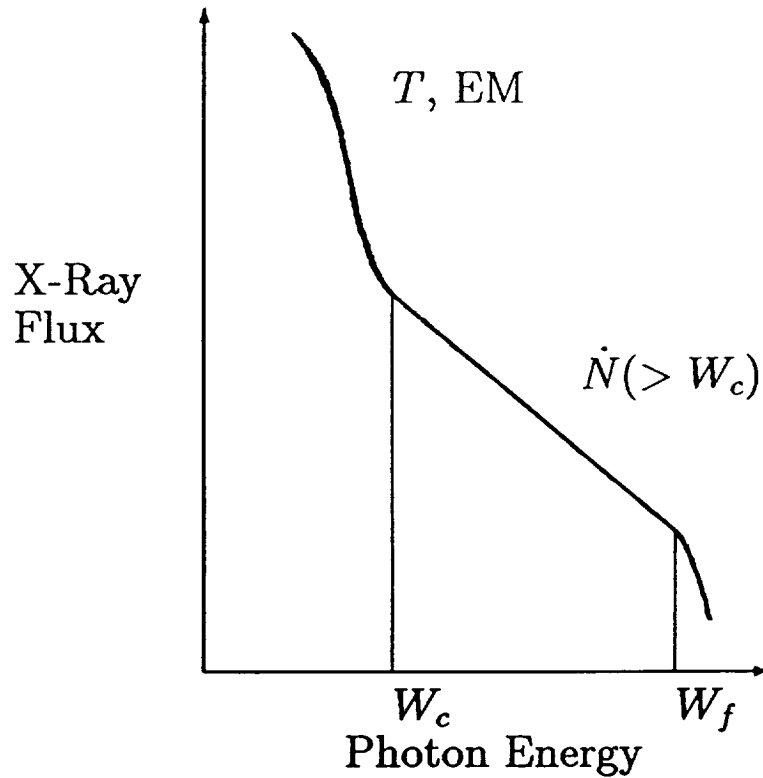
$$\begin{aligned} \dot{N} = 2.83 \times 10^{29} A_{18} B_2 T_7^{-1/2} s \nu_e \left(\frac{v_e}{v_d}\right)^{11/8} \exp\left\{-2^{1/2} \left(\frac{v_e}{v_d}\right)^{1/2} - \frac{1}{4} \left(\frac{v_e}{v_d}\right) \right. \\ \left. - \left(\frac{v_e}{c}\right)^2 \left[\frac{1}{8} \left(\frac{v_e}{v_d}\right)^2 + \left(\frac{2^{3/2}}{3}\right) \left(\frac{v_e}{v_d}\right)^{3/2}\right]\right\} \text{ electrons s}^{-1} \end{aligned}$$

The Ratio $\frac{\dot{N}}{Q}$ depends only upon T and $\frac{E_D}{E}$.

Energy Gained by Direct Electric Field Acceleration:

$$W_f - W_c = eEL$$

PHYSICAL PARAMETERS FROM X-RAY SPECTRUM



With a few basic assumptions, the following physical parameters can be deduced from a high-quality X-ray spectrum:

v_e	$\frac{E_D}{E}$ (and $\frac{\nu_e}{E}$)	$E_D L$ (and $\nu_e L$)
v_d	\dot{N}	Q

If classical resistivity, $\nu_e \propto n_s/T^{3/2}$, giving

$\frac{n_s}{E}$	and	$n_s L.$
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MINIMUM REQUIREMENTS FOR THE 1980 MAY 14 FLARE

If the hard X-ray emission is **thermal**, anomalous resistivity or densities exceeding $3 \times 10^{12} \text{ cm}^{-3}$ are required.

If the hard X-ray emission is **nonthermal**

and $T_s \sim 10^7 \text{ K}$, for $E \ll E_D$ very high heating rates ($\sim 10^{30} \text{ erg s}^{-1}$) are required.

and $T_s \sim 10^8 \text{ K}$, $E_D/E < 10$ and X-ray emission from the sheets is significant unless the resistivity is anomalous.

and $T_s \sim 4 \times 10^7 \text{ K}$, the emissions can be produced with classical resistivity if the heating rate is $\sim 4 \times 10^{28} \text{ erg s}^{-1}$, $n_s \sim 4 \times 10^{11} \text{ cm}^{-3}$, $E_D/E \sim 14$, and there are at least 10^4 current sheets.

Here T_s is the temperature in the current sheets.

(See Holman, Kundu, and Kane 1989, *Ap. J.*, in press, for details and other options.)

The soft and hard X-ray and microwave emissions can all be generated with sub-Dreicer electric fields and classical resistivity.

General Comments

- Electron acceleration/heating in current sheets provides a natural, determinable low-energy cutoff for the accelerated electrons.
- The energy input to direct heating will always exceed that to accelerated electrons as long as $E \ll E_D$.
- When the hard X-ray emission is predominantly nonthermal, a large number ($>10^4$) of oppositely directed current sheets is required. This is analogous to the fine-scale current/return current structures observed in the earth's auroral zone. The electrons can be accelerated in a "single" sheet if the resistivity in the sheet is highly anomalous and the particles escape the sheet on a length scale less than 10 km.